MICROWAVE PROPERTIES OF ALUMINUM OXY-NITRIDE FILM SUBSTRATES

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We measure the dielectric constant (ϵ_r) of a 50 μm thick aluminum oxy-nitride (AlON) substrate on a copper ground plane at both DC and microwave frequencies. Preliminary results indicate that $\epsilon_r = 10.97 \pm 0.24$ at DC and 10.86 ± 0.14 in the band of 1-20 GHz. The DC measurement relies on a capacitance technique, while the microwave measurement uses the reflection and transmission of microwaves in a microstrip resonator structure. Additionally, we present current testing that demonstrates that the quality of our manufacturing techniques and the thermal conductivity of the substrate are adequate to produce microwave atom chips.

INTRODUCTION

At William and Mary's Ultracold Atoms Lab we are developing an atom chip designed to harness microwaves to utilize the AC Zeeman (ACZ) effect to make Bose-Einstein Condensates (BEC) and Degenerate Fermi Gases (DFG) for use in atom interferometry. Current atom chips used to trap neutral atoms operate using the DC Zeeman effect (DCZ). Microwave atom chips have several advantages over DCZ atom chips. They allow for spin-specific trapping, the creation of multiple traps simultaneously, and the ability to spatially separate the traps. These are the tools that open the door to robust atom interferometry experiments that will allow us to make precision measurements of local gravity, electric and magnetic fields, inertial rotations as well as the Casimir-Polder force and even sub-millimeter gravity.

From an engineering perspective, the primary difference of an atom chip that operates on the ACZ effect vs the DCZ effect is the need to impedance match [1]. This allows the mode of the microwaves to transition smoothly from the transmission cables to the microstrips on the chip. Impedance matching is primarily dependent on the thickness of the dielectric substrate, dielectric constant of the substrate, and the width of the microstrip. We are using a 50 μm substrate of AlON. We then need to find the effective dielectric constant (ε_r) of that substrate so we know how wide to make the microstrips. In this paper I will discuss the work I have done to find the ε_r of the AlON in our substrate, both at DC and in the microwave regime.

METHODS

For our experiments, we diced sheets of copper-aluminum nitride-copper (Cu-AlN-Cu) sandwiches into several 15 mm × 35 mm samples and 22 mm × 35 mm samples. In addition to these, we used four 30 mm × 30 mm and three 50mm × 50 mm samples with 2 mm thick solid Cu. Each of these samples had one side diamond turned to reduce roughness and increase planarity. Our partners at Global Nitride then deposited aluminum oxynitride (AlON) on the diamond turned surface. This occurred in two runs. The first deposition run created an AlON substrate of approximately 46 µm. The second run gave us an AlON substrate of approximately 50 µm. Roughly half of the samples had 5 µm Cu sputtered on top of the AlON substrate.

We have two methods for creating microstrips or other metal structures on our substrates. For the samples with Cu deposited, we etch away the Cu to create microstrips. For the samples with a bare substrate, we deposit Silver (Ag) onto the substrate to create microstrips.

A. DC Measurements

Two of the 30 mm × 30 mm samples and two of the 50 mm × 50 mm samples had 5 µm of Cu on top of the AlON substrate. Using a multimeter at William and Mary, we measured the capacitance of these samples. For each sample, we took several measurements at different positions along the plates. The multimeter provided settings to test the capacitance at 100 Hz, 120 Hz, and 1000 Hz and we performed our testing using all three settings. Once we obtained a capacitance measurement, we were able to calculate the dielectric constant by using the equation for capacitance $C = \frac{\varepsilon_0 \varepsilon_r A}{d}$ to find the dielectric constant at DC as seen in figure 1.

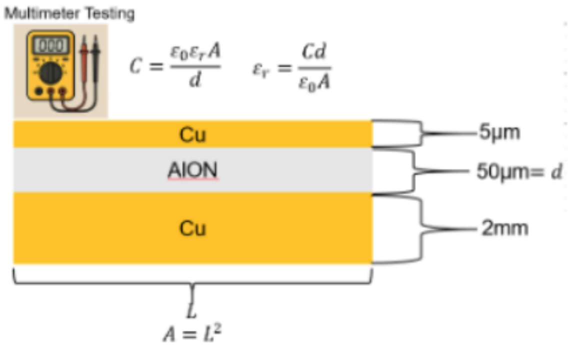

Figure 1:Four samples provided capacitance measurements. From these, we were able to calculate the dielectric of AlON at DC.

B. Microwave Resonators

Our interest in AlON is to be a substrate for a microwave atom chip. Our primary interest is in the effective dielectric constant in the microwave regime. We accomplished this using resonators. The resonators consisted of metal, either deposited on the AlON substrate or etched away from the 5 µm Cu substrate. There is a central cavity fed by narrow microstrips at either end as seen in figure 2 (a) and (b). The length of the cavity must be at least an order of magnitude greater than the width to avoid measuring transverse reflections. The theory behind the resonators is that an AC (microwave) signal is sent into the cavity and reflected off the far walls at either end of the length. We then measure the frequency difference between the resonances of the S parameters as measured by a vector network analyzer (VNA) from 1 GHz to 20 GHz, as seen in figure 2(d). The relationship between the frequency difference and the length is

$$\Delta \text{f} = \frac{v}{2L} \tag{1}$$

where v is the microwave velocity. While the AC current travels through the microstrip, the EM field generated by the current travels through the substrate itself, therefore the velocity of the microwave is inversely related to the effective index of refraction of the dielectric material,

$$v = \frac{c}{n_{eff}} \tag{2}$$

The index of refraction is related to the dielectric constant by,

$$n_{eff} = \sqrt{\alpha \varepsilon_r} \tag{3}$$

where α is a constant dictating the effective index of refraction in the operating environment and must be determined by simulation. Substituting equations 2 and 3 into equation 1 and solving for the dielectric constant gives us,

$$\varepsilon_r = \frac{1}{\alpha}\left(\frac{c}{2L\Delta \mathrm{f}}\right)^2 \tag{4}$$

This is an iterative process. To find α we run a simulation of the resonator geometry using our best guess for the dielectric constant. From the simulation, we get a frequency difference. Using this with the dielectric constant used in the simulation, we rearrange equation 4 to calculate α. Then we can use α to obtain a dielectric constant from the VNA data which is used in a further simulation to refine α. This process is repeated until the value of the dielectric constant is shown to be constrained, typically after two or three iterations.

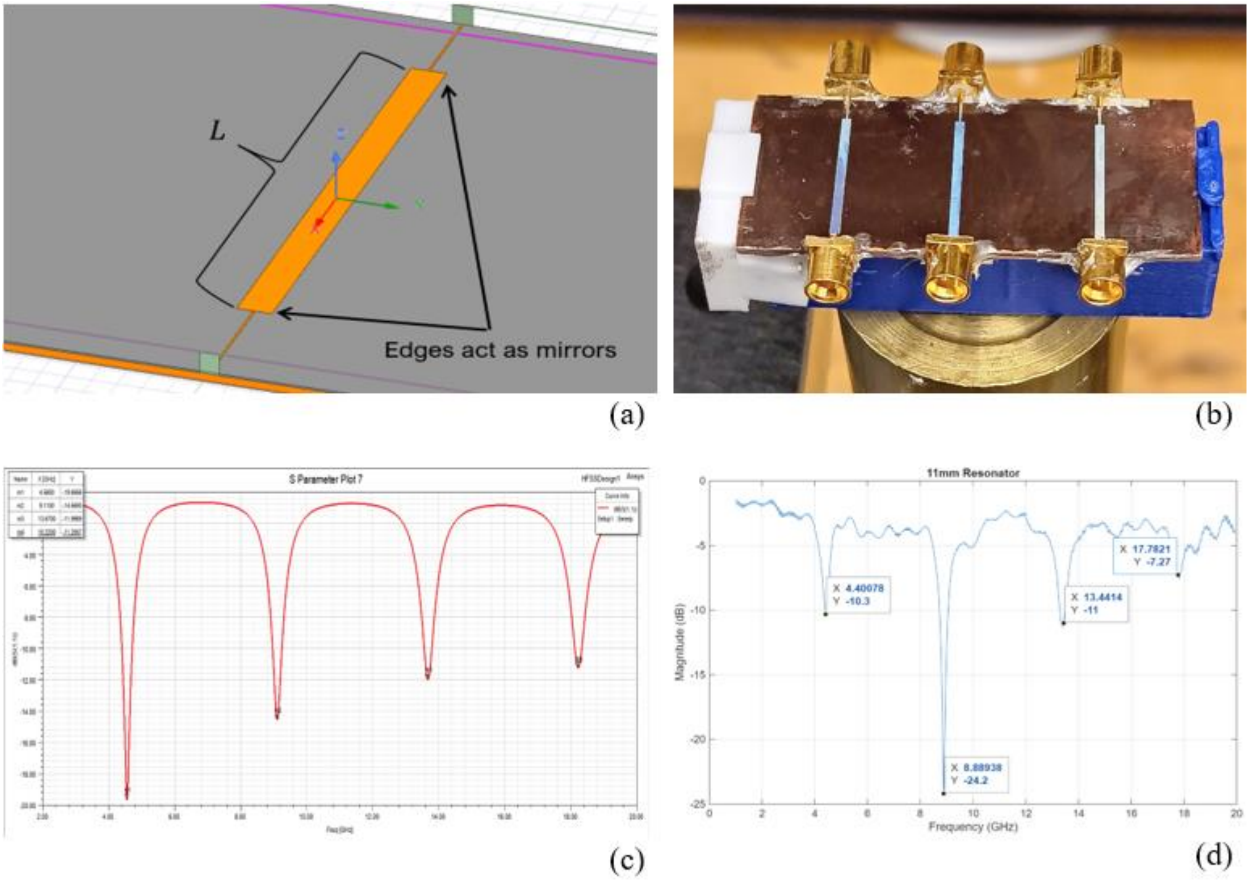

Figure 2: The iterative process of finding the dielectric constant using resonators. ***(a)*** *An HFSS model simulating a 0.7 mm × 11 mm resonator cavity.* ***(b)*** *A 15 mm × 35 mm chip with AlON substrate and three 0.7 mm × 11 mm resonator cavities used in testing.* ***(c)*** *HFSS simulation results from the model in figure (a) using* $\varepsilon_r = 11$ *(d) Results from testing one of the resonators in figure (b) on a VNA.*

C. DC Current Testing

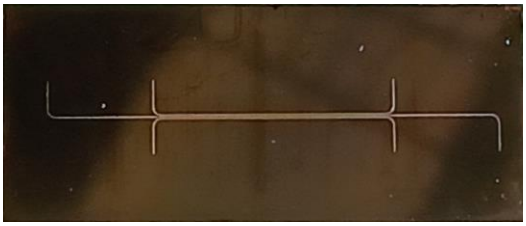

Figure 3: Three microstrips on an AlON substrate, two U wires and a central Z wire. These microstrips used deposited Ag with adhesion layers of Cr and Ti.

After successfully depositing Ag for three microstrips on a 15mm × 35 mm sample as seen in figure 3, we tested the adhesion of the metal to the substrate. An initial test was performed on the resonators to test adhesion by trying to remove the metal using scotch tape. This was unsuccessful on all samples made using deposited Ag. Five out 6 Cu etched resonators passed the tape test. A more thorough evaluation was performed by running a DC current through the microstrips in shown in figure 3 to determine the maximum current the microstrips can handle before burning out. Before explaining the course of these tests, let us discuss the manufacturing process for the microstrips and resonators.

We based our formula after previous work performed at the university of Toronto to make DCZ atom chips, one of which is used in our lab today [2]. We use 200 nm of chromium (Cr) and 400 nm of titanium for adhesion layers. We ultimately want a microstrip thickness of 5 µm, but the sample shown in figure 3 is a test and only used 2.4 µm of silver for an expected thickness of 3 µm. The tooling factor on the electron-beam evaporator appears to be inaccurate, because we measured the final thickness around 3.8 µm in the figure 3 sample. The microstrips were 54 µm wide. This dimension was based on research and simulations that assumed a dielectric constant comparable Aluminum Nitride. While this does not reflect the actual final width we expect to use, it is close to this value and is good enough for an initial attempt.

We used four-point resistance measurement protocol when performing the current tests. For the first test on the central Z wire, we taped the sample to a breadboard as seen in figure 4. We stripped the cladding from spare stranded wire in the lab and cut away a single strand. To make contact between the microstrips and the probe wire, we used conductive glue. The other side of the cut strand of wire was soldered into the breadboard so we could use standard probes with tabletop multimeters to track the current and voltage during tests.

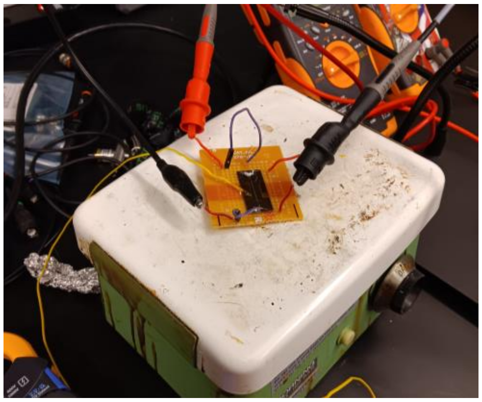

Figure 4: Initial four-point test of the Z wire. The multimeters shown were switched out with more precise tabletop multimeters.

We began the test by running a 0.1 A current through the wire and pushed the current up incrementally by 0.1A per test. Higher current heats the microstrips which results in higher resistance. By tracking the current and voltage we were able to track the resistance as it went up with increased current. Atom chips are heat sunk in practice to allow them to maximize the current used in experiments. We did not heat sink the sample during the Z wire test and found the wire would become quite hot before saturating. We added a fan to the experiment, but this was inadequate.

For testing the two U wires we glued the sample to a Cu block to improve the removal of heat from microstrips. This helped the resistance measurements saturate much faster than in the Z wire case. For the first U wire test we began testing at 0.5 A and increased in 0.5 A intervals up to 2 A. The plan was to increase the current at 0.1 A intervals from there, however, the wire unexpectedly burnt out at this level. For testing the second U wire we began at 0.5 A and increased the current in 0.5 A intervals to 1.5 A then began increasing the current by 0.1 A intervals. This proved to be yield better data.

III. RESULTS

A. ε_r at DC

We were able to test three samples with a variety of dimensions to find the dielectric constant using a handheld multimeter. The results are shown in table 1. These tests helped establish a base line dielectric constant to use in simulations for resonator testing.

Sample	ε_r	Error
3cm×3cm Run 2	10.6	±0.21
5cm×5cm Run 1	10.9	±0.19
5cm×5cm Run 2	11.4	±0.23
Average	**10.97**	**±0.24**

Table 1: Three samples with the dielectric constant at DC found from capacitor testing.

B. ε_r for Microwaves

As of this paper, we have completed testing on four resonators. One with a cavity of 0.7mm × 11 mm and three with 1 mm × 25 mm cavity. Table 2 lists the results of these tests.

Resonator	ε_r	Error
res_{11}	10.85	±0.15
$res_{25.1}$	11.16	±0.04
$res_{25.2}$	10.89	±0.16
$res_{25.3}$	10.52	±0.21
Average	**10.86**	**±0.14**

Table 2: The dielectric constant with error from four resonator tests ranging from 1GHz to 20GHz. The final row gives the average of the four tests with the standard error of the mean of those tests.

C. Current Test Results

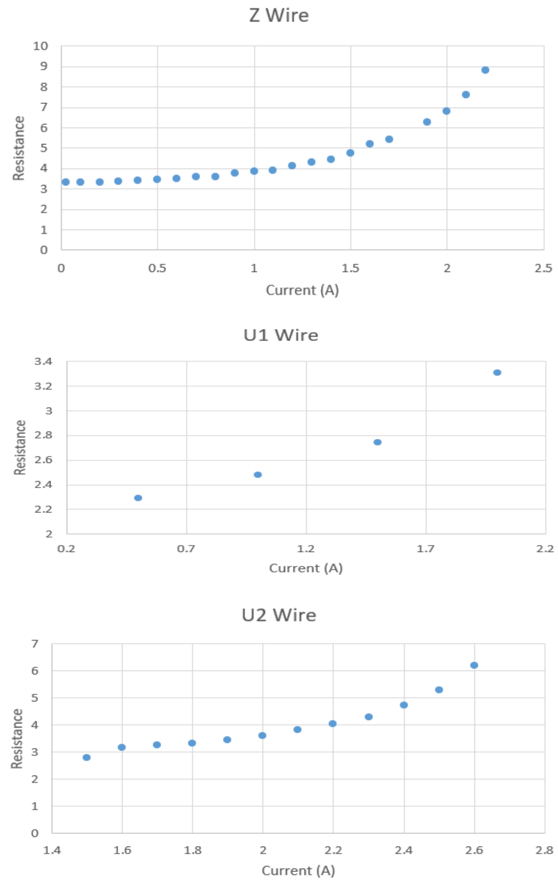

Figure 5: Current testing on the three microstrips shown in figure 3. The Z wire burned out at 2.4 A, U1 at 2 A, and U2 at 2.7 A.

Figure 5 shows the plots for the three current tests on Ag microstrips deposited on an AlON substrate. The rise in resistance is due to the increased current resulting in higher temperatures. The temperature rise is proportional to the rise in resistance, but due to instabilities in the conductive glue used to connect to the microstrips we were unable to calibrate the resistance to the temperature. Our greatest concern was the current level at which we burned the microstrip. The current source used during tests produced voltage fluctuations when first initiated. Each microstrip burned out during this fluctuation which is why there is no final data point in the Z wire or in the U2 wire. We performed more than one 2 A test on U1 which is why we have the final data point for that microstrip. This 2 A current level marks the minimum current the microstrips could handle. Given the microstrip dimension at the point of burn out this gives us a minimum current density of $1.32 \times 10^6\ {}^{A}/_{cm^2}$

IV. Conclusion

Having achieved a minimum of 2 A in current testing ensures that the thermal conductivity of AlON is high enough for our uses as a dielectric for the microwave atom chip. It also indicates that our deposition procedure offers robust adhesion to the substrate.

The dielectric constant is the final puzzle piece needed to move into full atom ship production mode. The data collected indicates a preliminary value of, $\varepsilon_r = 10.86$.

We have several more resonators ready to be tested. There is some expectation the final value may be somewhat higher than our current result. This work should be completed soon. With confidence in the dielectric value, we will know how wide to make our microstrips for the atom chip. Our manufacturing methods are proven for individual components. The next step coupling the components of the chip together and testing as a unit.

V. Acknowledgements

We would like to thank NSF for the funding of this research as well as our partners at Nitride Global who deposited the AlON substrate for our samples. Much of the design work for the microwave atom chip was completed by Dr. William Miyahira and early resonator research was conducted by Jordan Shields. Finally, we would like to thank the Virginia Space Grant Consortium for their support.

VI. References

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